The Mars 2020 Lander Vision System: Architecture and V&V Results

IPPW 209

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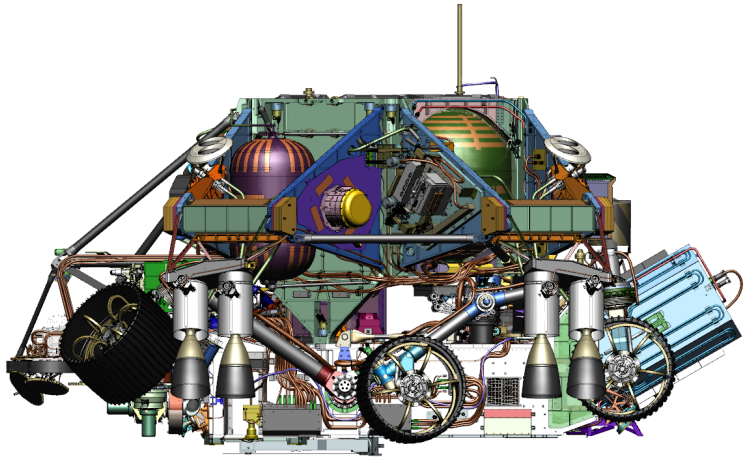
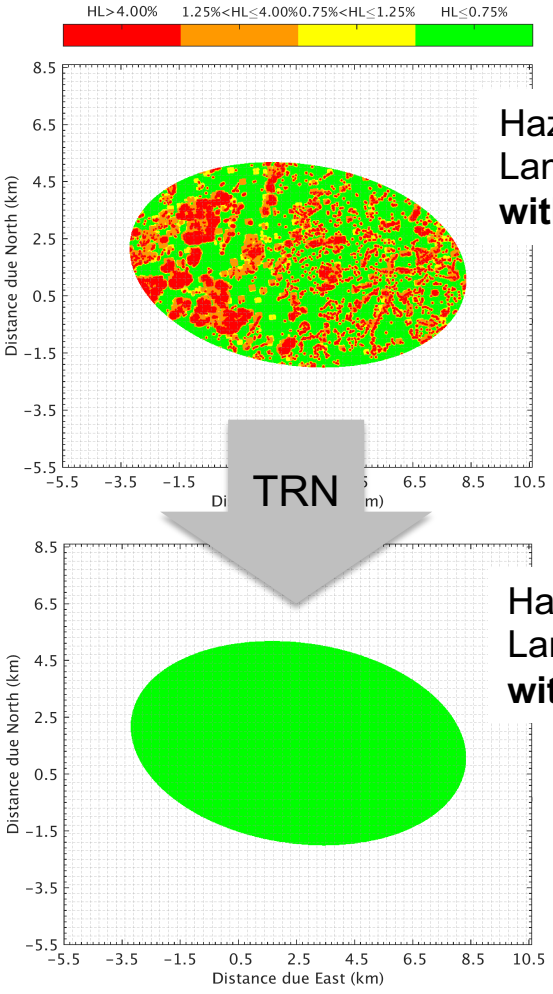
9 July, 2019



Mars 2020 Project

Terrain Relative Navigation

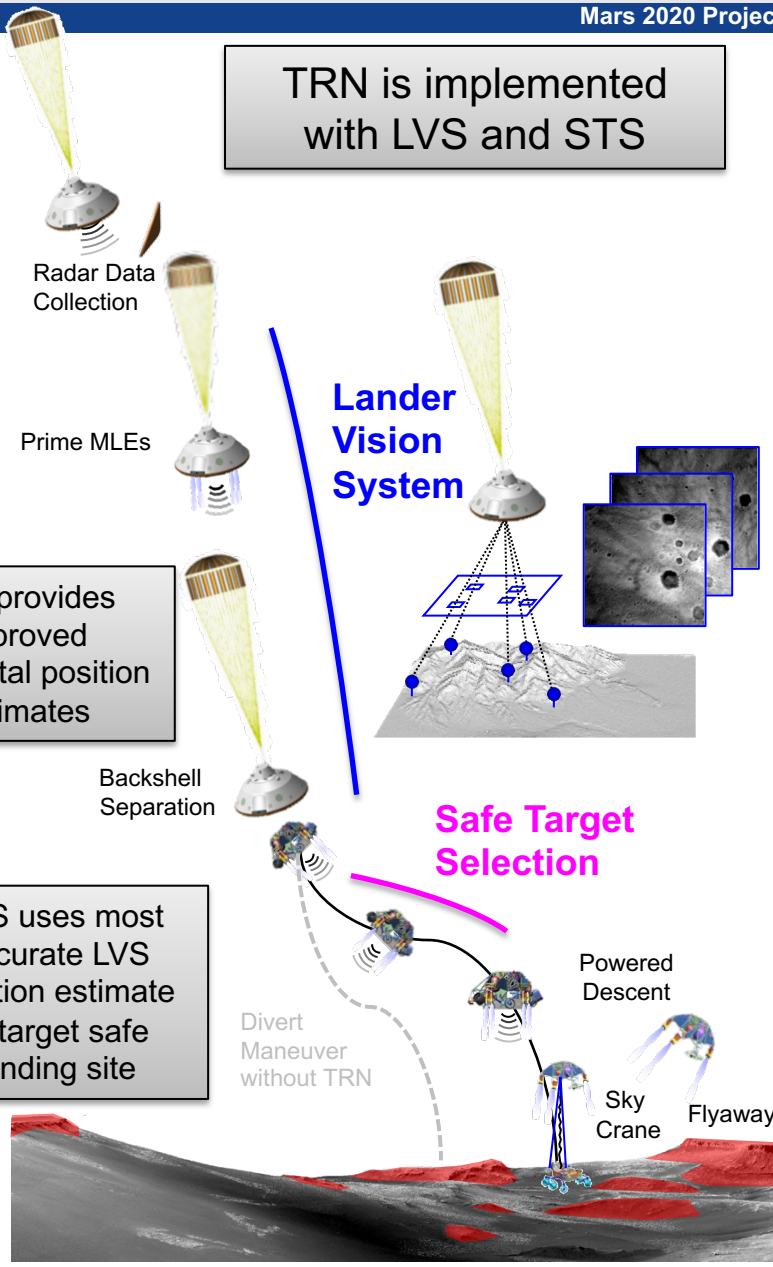
TRN enables access to hazardous landing sites



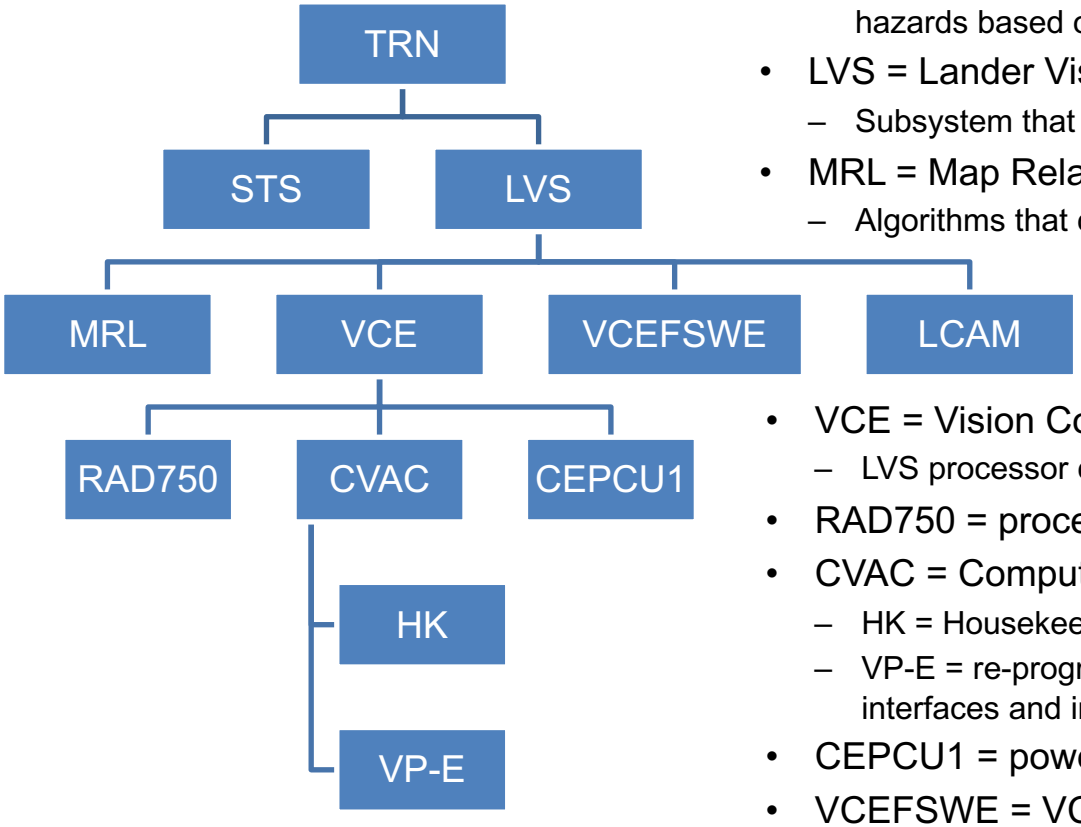
Hazards in Landing Ellipse **without TRN**

Hazards in Landing Ellipse **with TRN**

TRN is implemented with LVS and STS



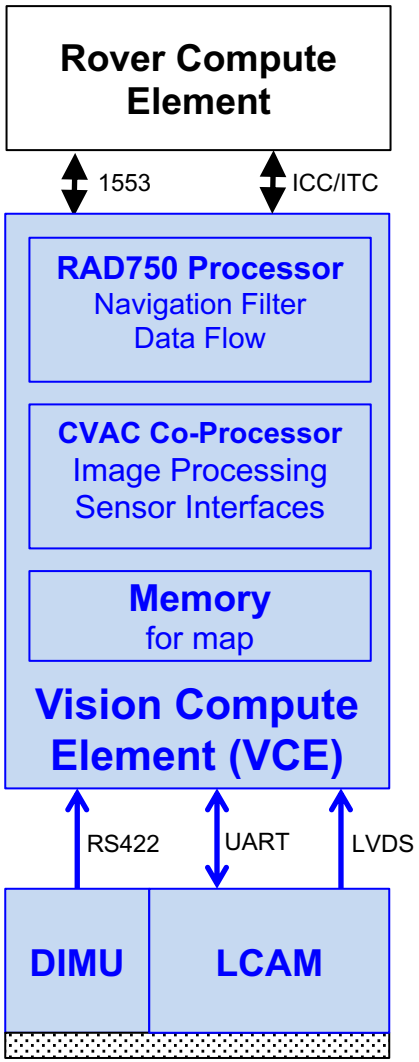
TRN Component Architecture

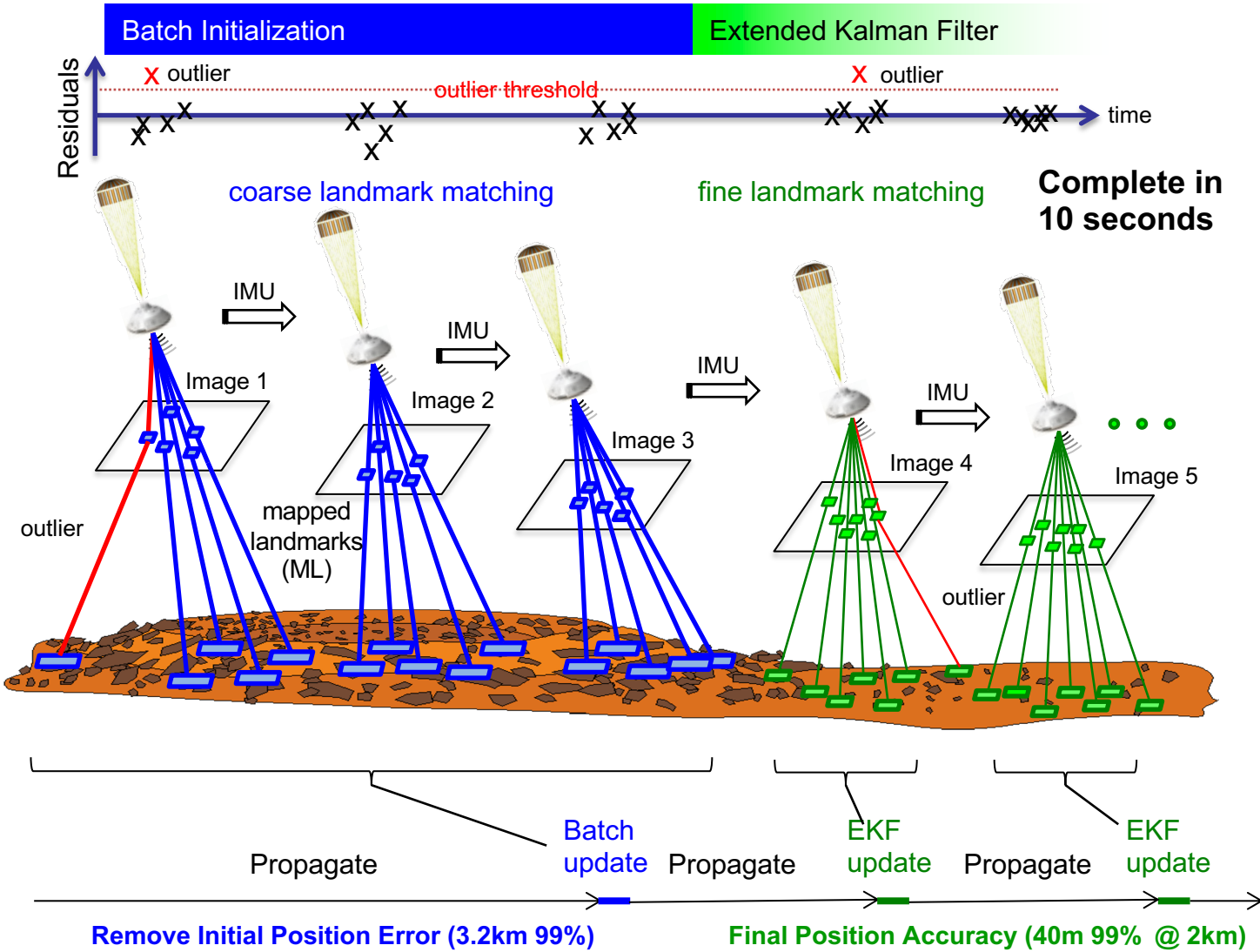


- TRN = Terrain Relative Navigation
  - The overall system that enables the avoidance of known hazards in the landing ellipse
- STS = Safe Target Selection
  - Subsystem that picks the safe landing site between a-priori hazards based on the position provided by LVS
- LVS = Lander Vision System
  - Subsystem that performs Map Relative Localization
- MRL = Map Relative Localization
  - Algorithms that compute position relative to a map

- VCE = Vision Compute Element
  - LVS processor containing three cards
- RAD750 = processor card
- CVAC = Computer Vision Accelerator Card
  - HK = Housekeeping FPGA on CVAC
  - VP-E = re-programmable Virtex5 FPGA on CVAC with sensor interfaces and image processing
- CEPCU1 = power conditioning card
- VCEFSWE = VCE Flight Software for EDL
- LCAM = LVS Camera, procured from Malin Space Science Systems

Lander Vision System (LVS) Overview





Vision Compute Element

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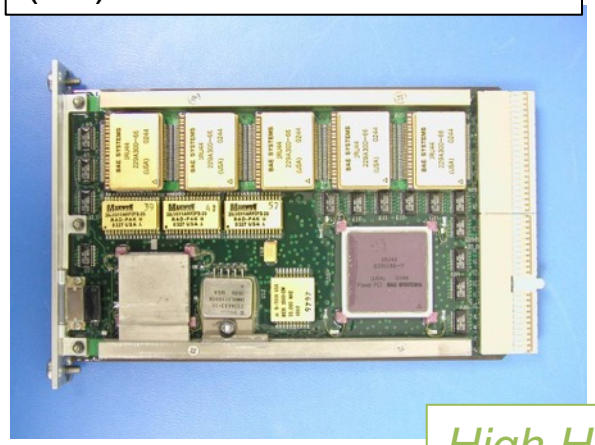
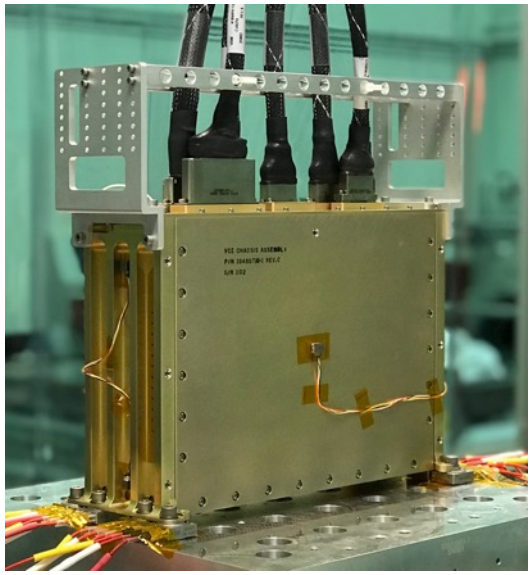
Flight RAD750 Processor (3U) 132Mz Version



Flight CEPCU1 power conditioning card (6U)

High Heritage

6U cPCI 3 slot chassis and backplane



New Computer Vision Accelerator Card (CVAC) (6U)

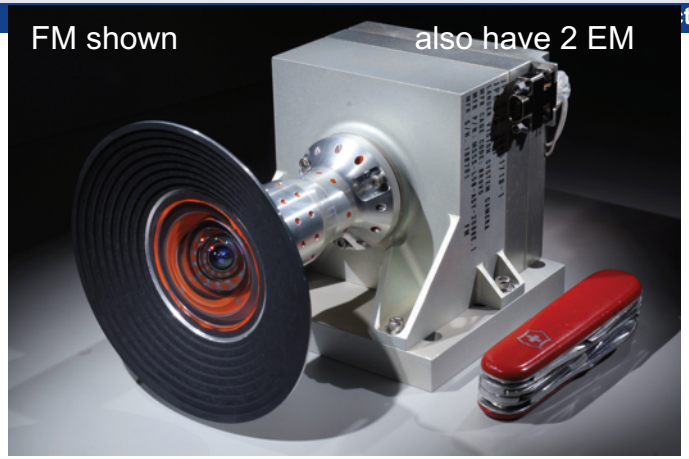
Assembly Name: M2020 VCE CVAC Top Assembly
P/N: 10480740-1 S/N: 101, Rev: C
Hardware Type: Flight State of the Assembly: Rework
IBAT# : 640350, Step 60 Date: 18-OCT-2018

- **VCE delivered and mechanically integrated with the spacecraft**
- The Vision Compute Element (VCE) is a 3 slot 6U processor
  - BUILD TO PRINT: RAD750 general purpose processor
  - BUILD TO PRINT: power conditioning card VCEPCC)
  - NEW: Computer Vision Accelerator Card (CVAC)
    - RTAX2000 housekeeping FPGA
    - reprogrammable Virtex5 FPGA
    - heat strap for thermal management
    - flash memory

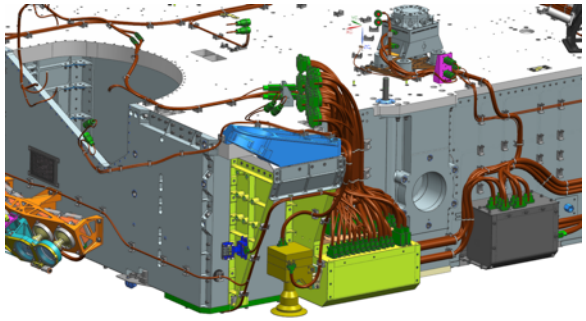
LVS Camera

Jet Propulsion Laboratory
California Institute of Technology

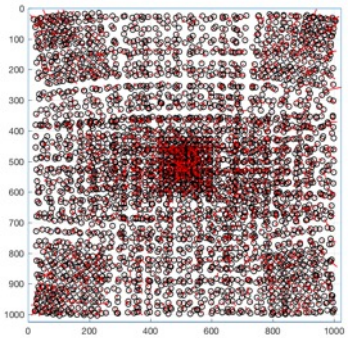
- **LCAM delivered to spacecraft integration**
- LCAM Built by a Malin Space Science Systems
  - proven Mars camera vendor
- LCAM Specs
  - 1024 x 1024 pixels, 89˚ x 89˚ FOV
  - 480nm-720nm sensitivity
  - <100 msec image latency, 300us exposure time
  - 8-bit per pixel, >70 signal-to-noise ratio
  - -40C to +70C qual temp
  - power <4.0W, mass 0.865 kg



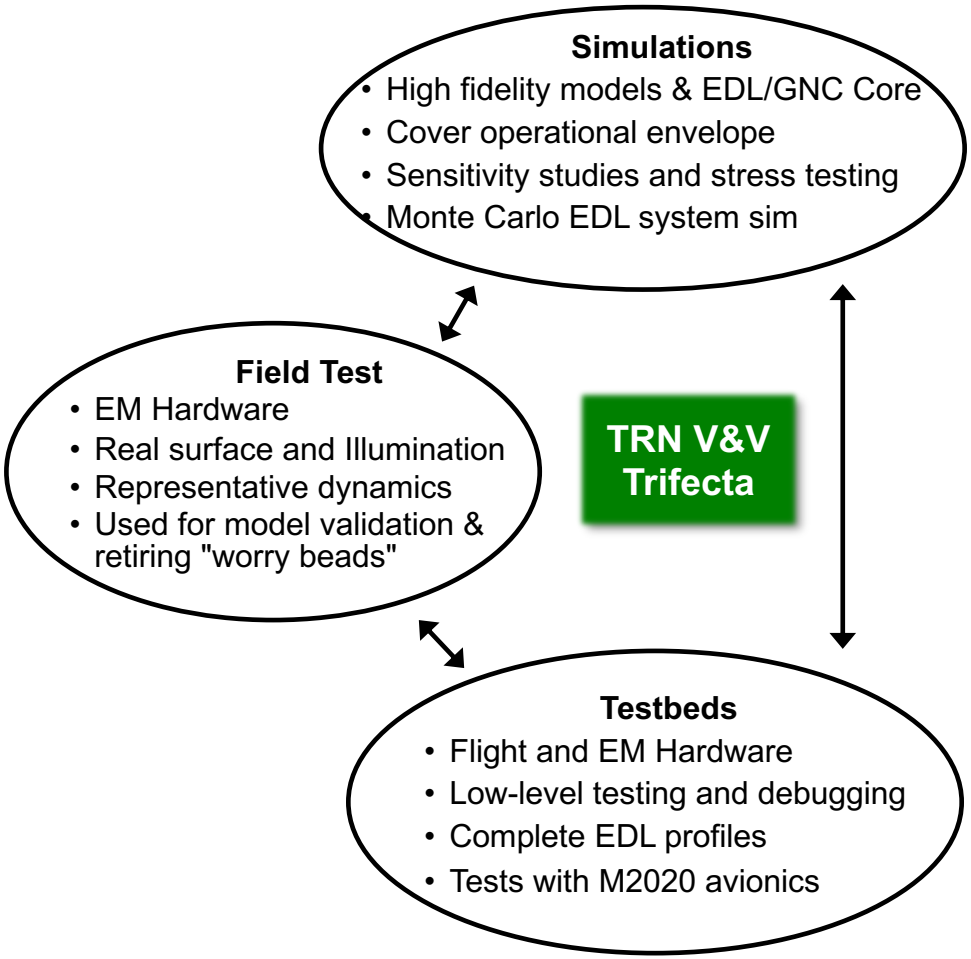
placement on rover



geometric calibration residuals

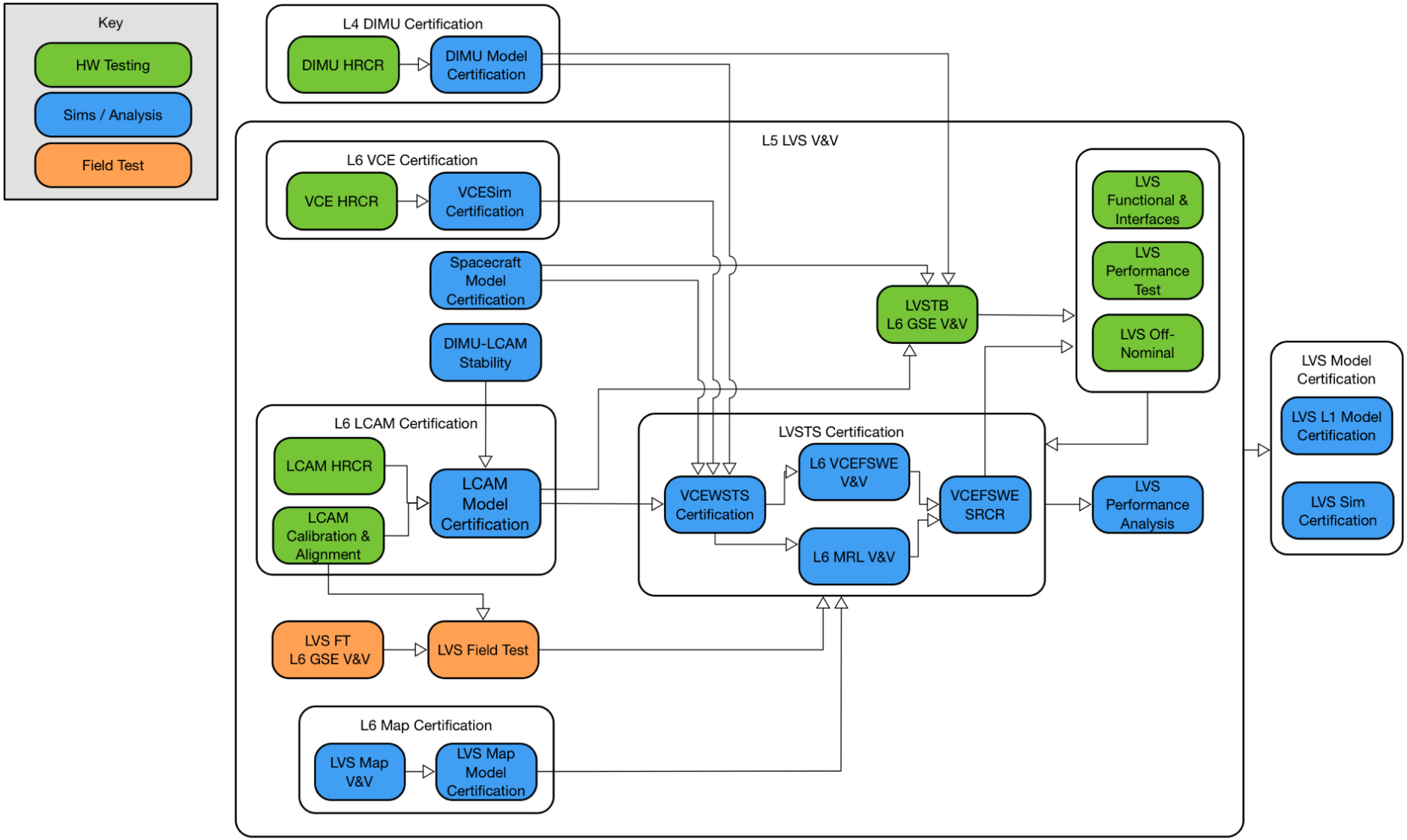


TRN V&V Approach



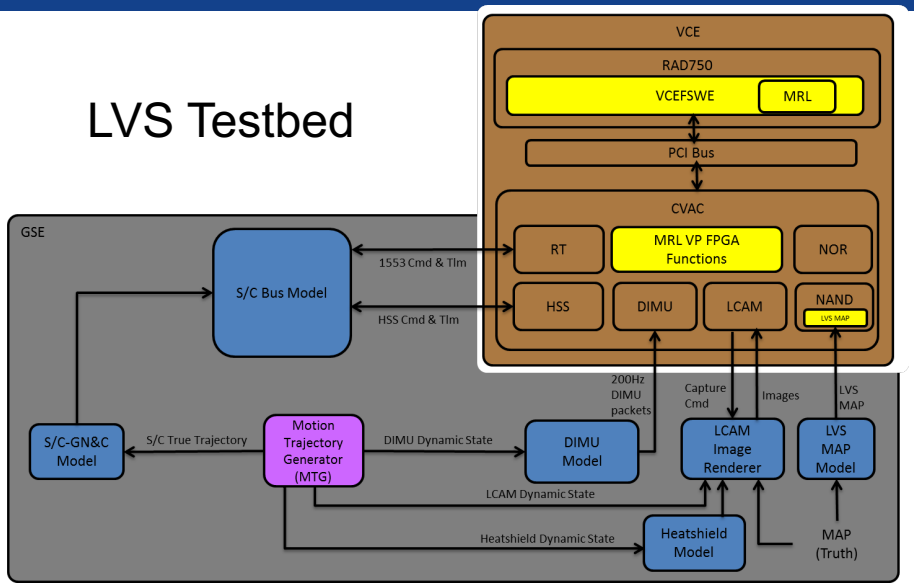
- Based on TDS V&V program, same "Trifecta" approach
- Testing philosophy
  - Test As You Fly (TAYF)
  - Stress Testing
  - Worry Beads
- Varying degrees of hardware and software behavioral fidelity
  - LVS, LCAM, and map models
  - EDL/GNC FSW Core (incl. STS)
  - From LVSTS through flight HWIL
- Validation
  - Field tests
  - Multiple Mars datasets

L5 – L6 V&V Relationships



LVS I&T/V&V Venue Overview

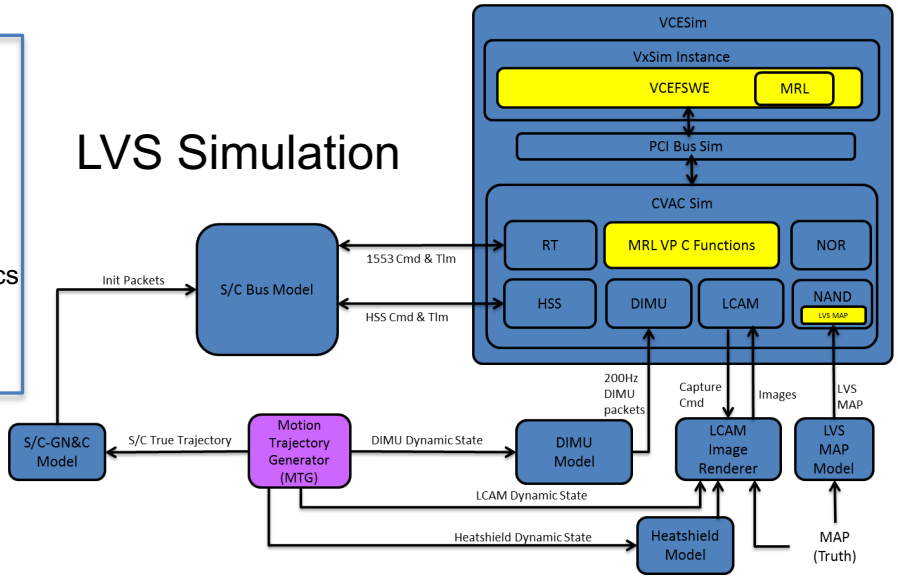
LVS Testbed



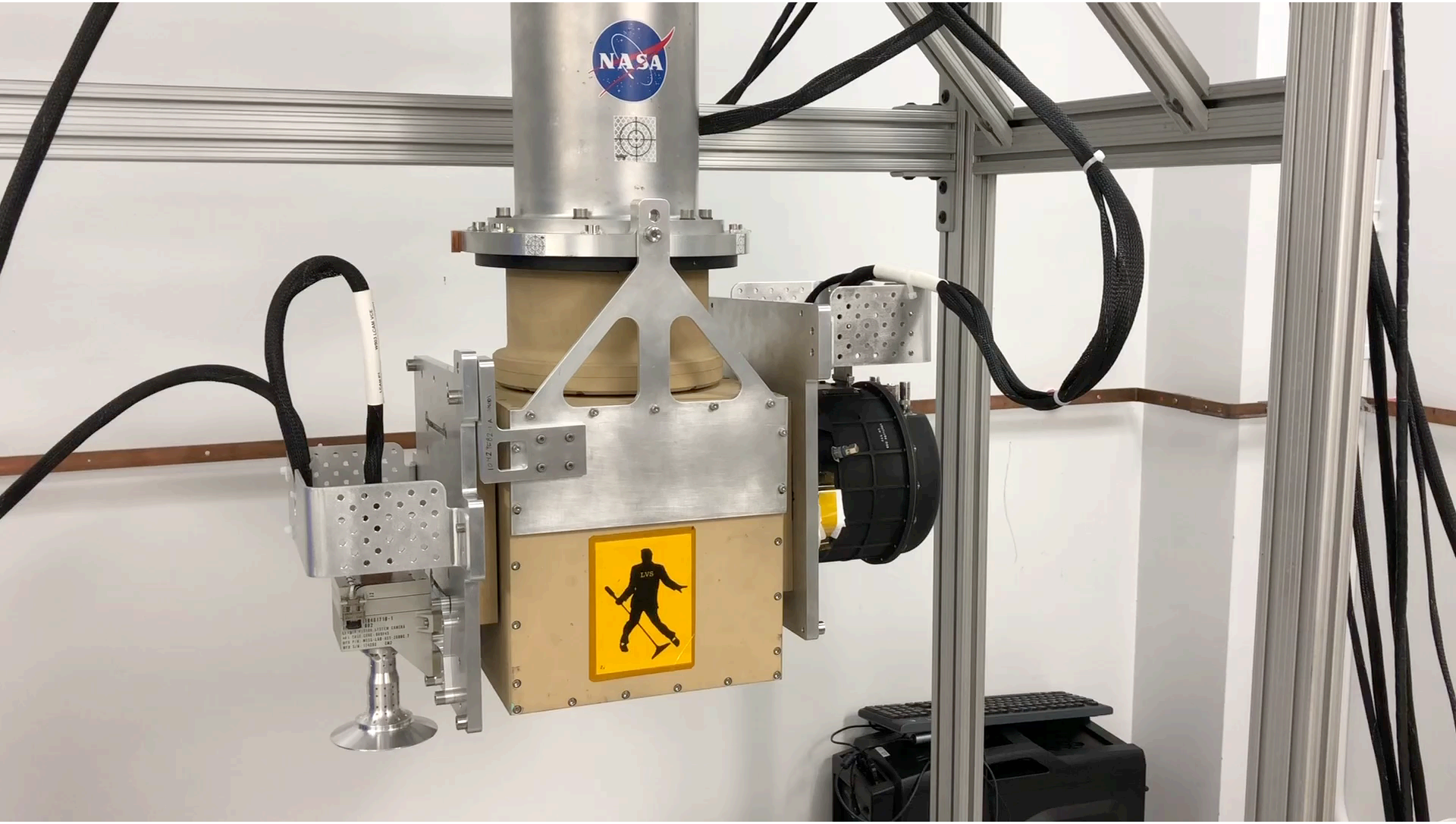
LVS "Elvinator"

HW
SW
model
dynamics
GSE

LVS Simulation

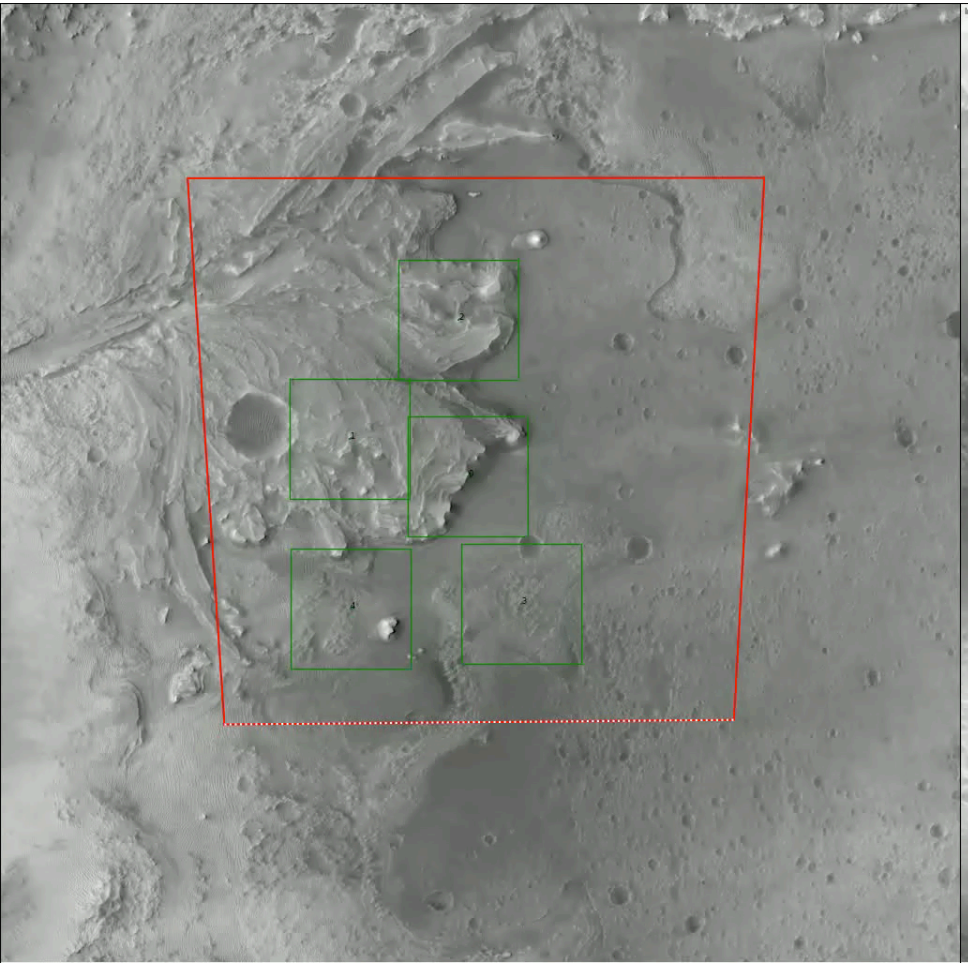


”Elvinator” with Gimbal Moving

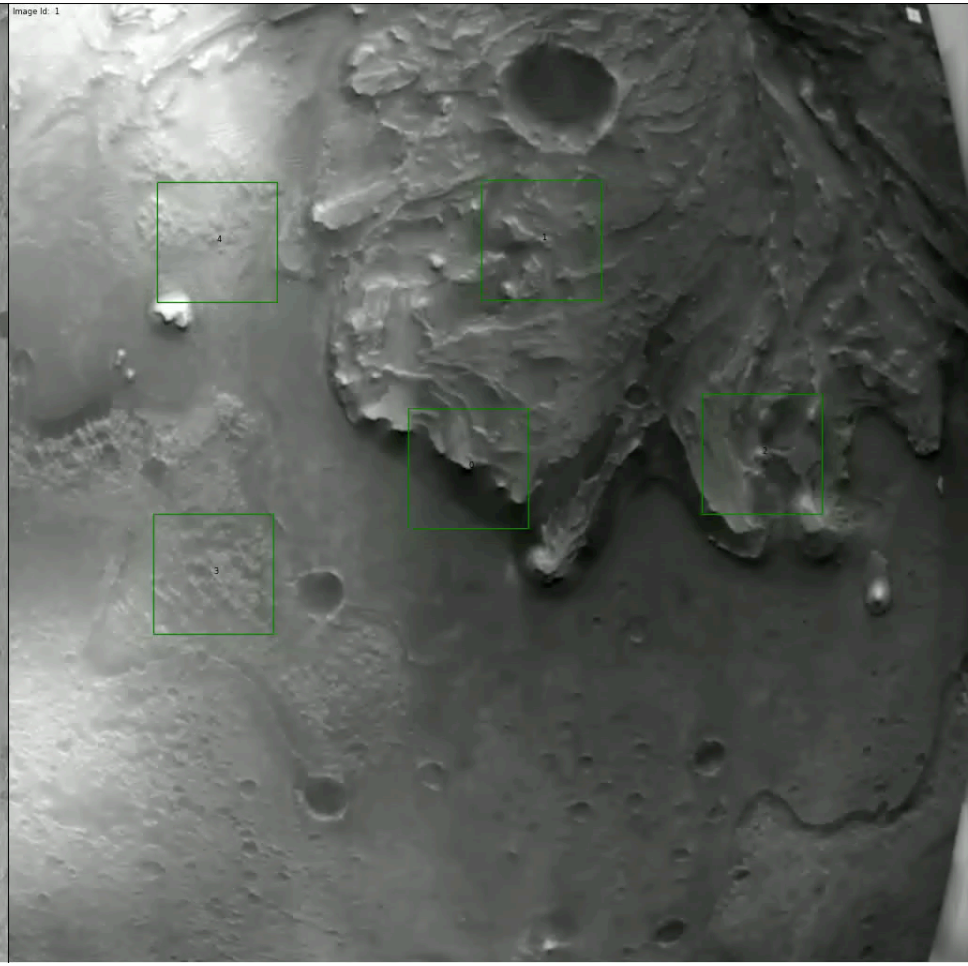


Landmark Matches with Gimbal Moving

Map
(cropping of larger map happens for every fine image)

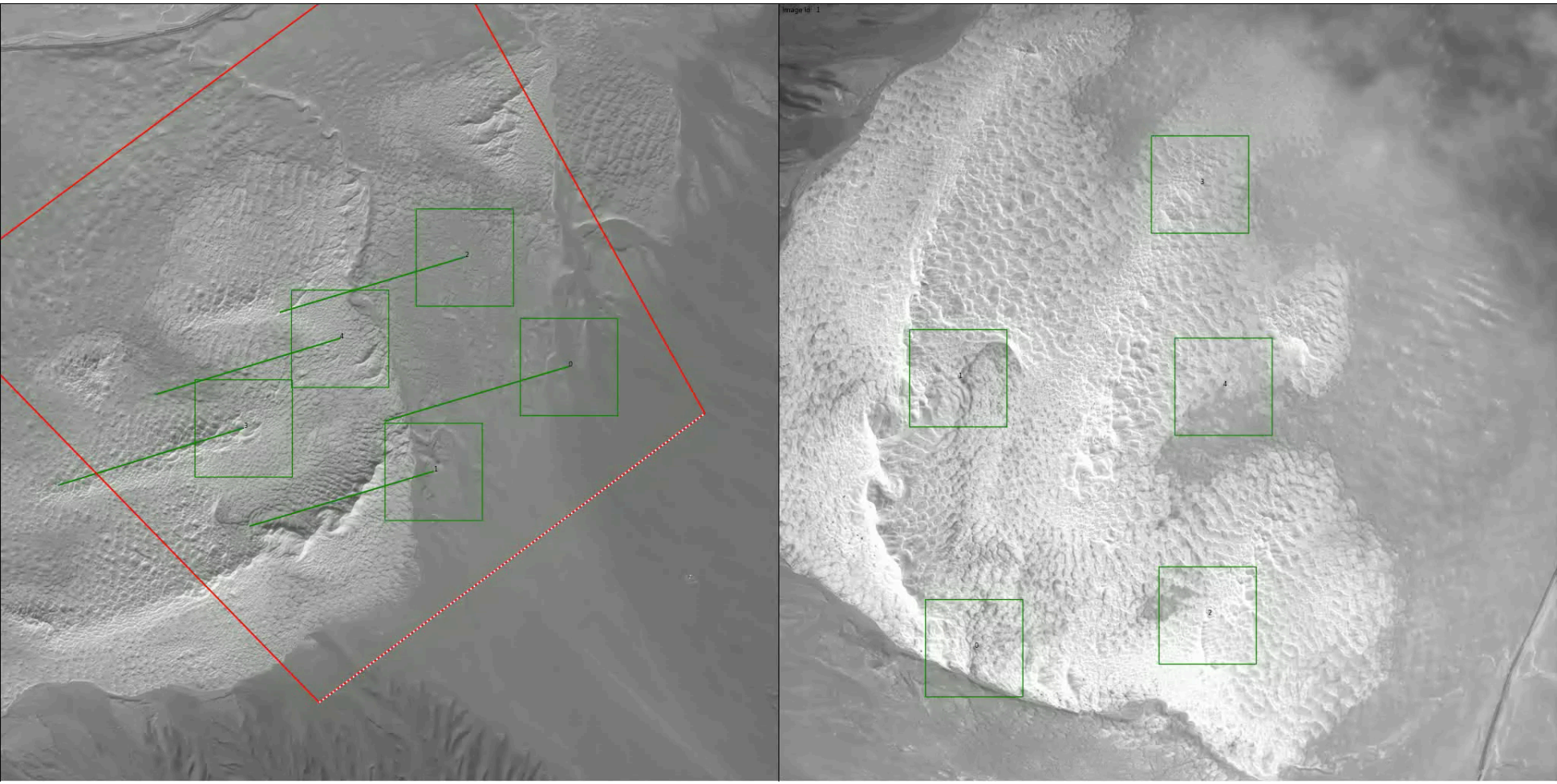


LCAM Image
(motion on gimbal)

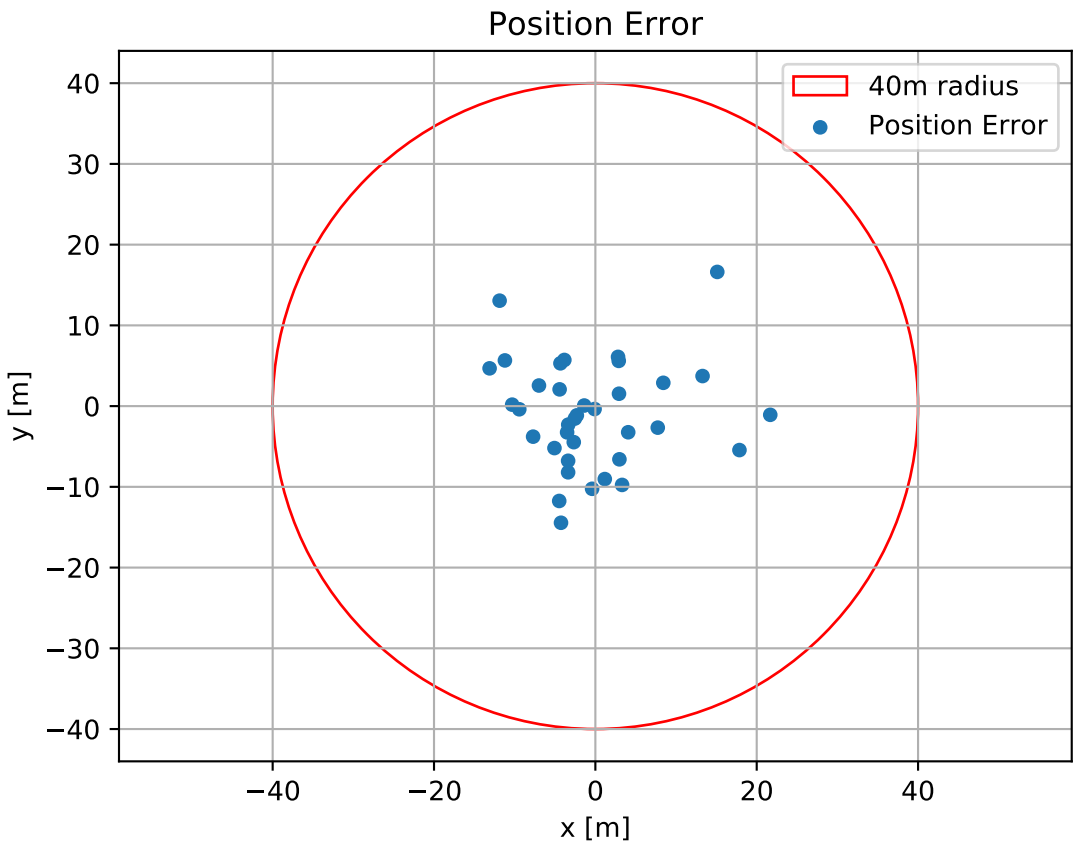


Helicopter Test Flight – Death Valley
May 20, 2019

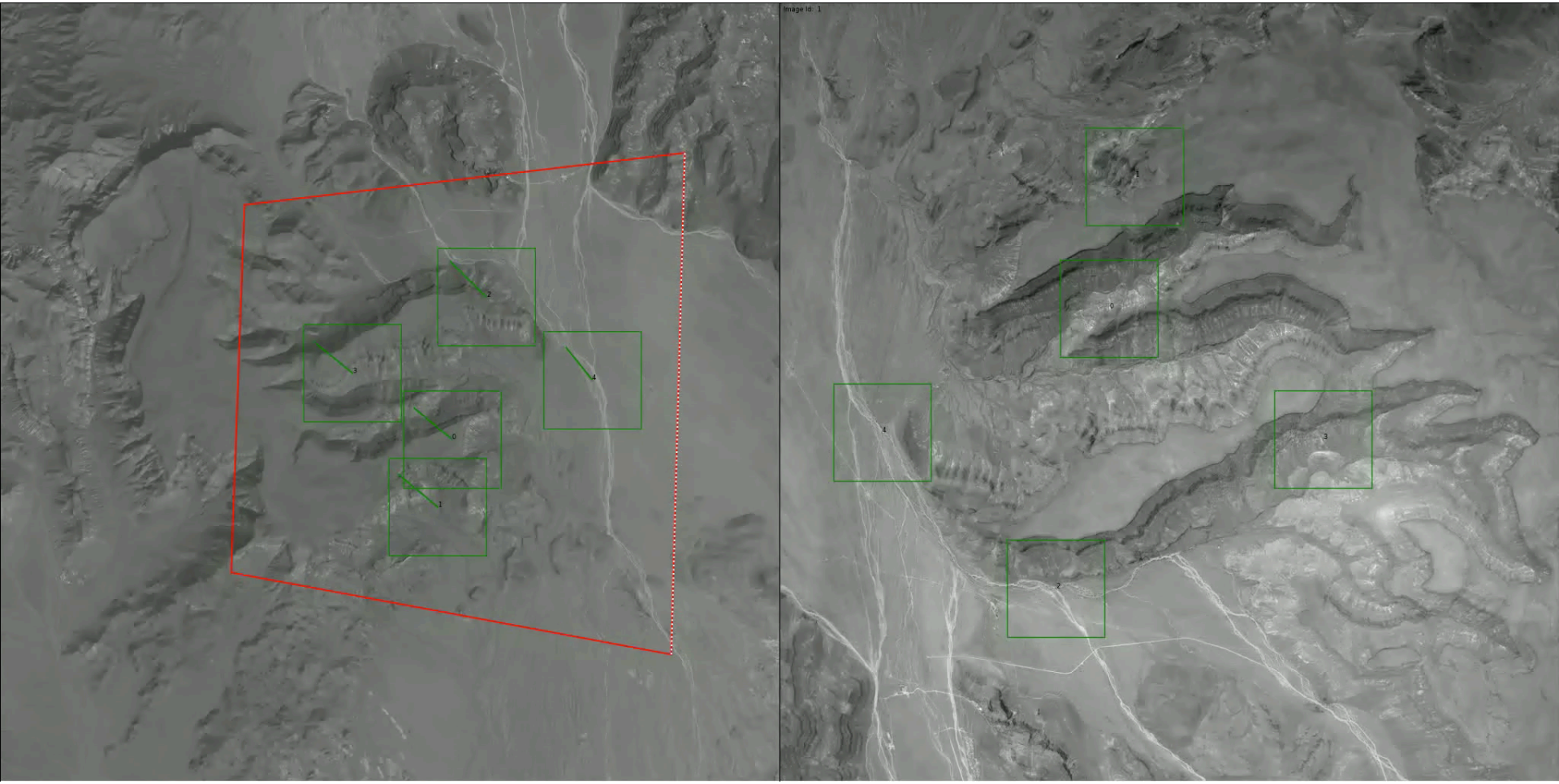
Kelso Sand Dune Result AM (KSD_03)



Example Position Error Scatter Plot: Kelso Sand Dunes AM (KSD_03)



Hole In Wall Example over 300m Cliffs

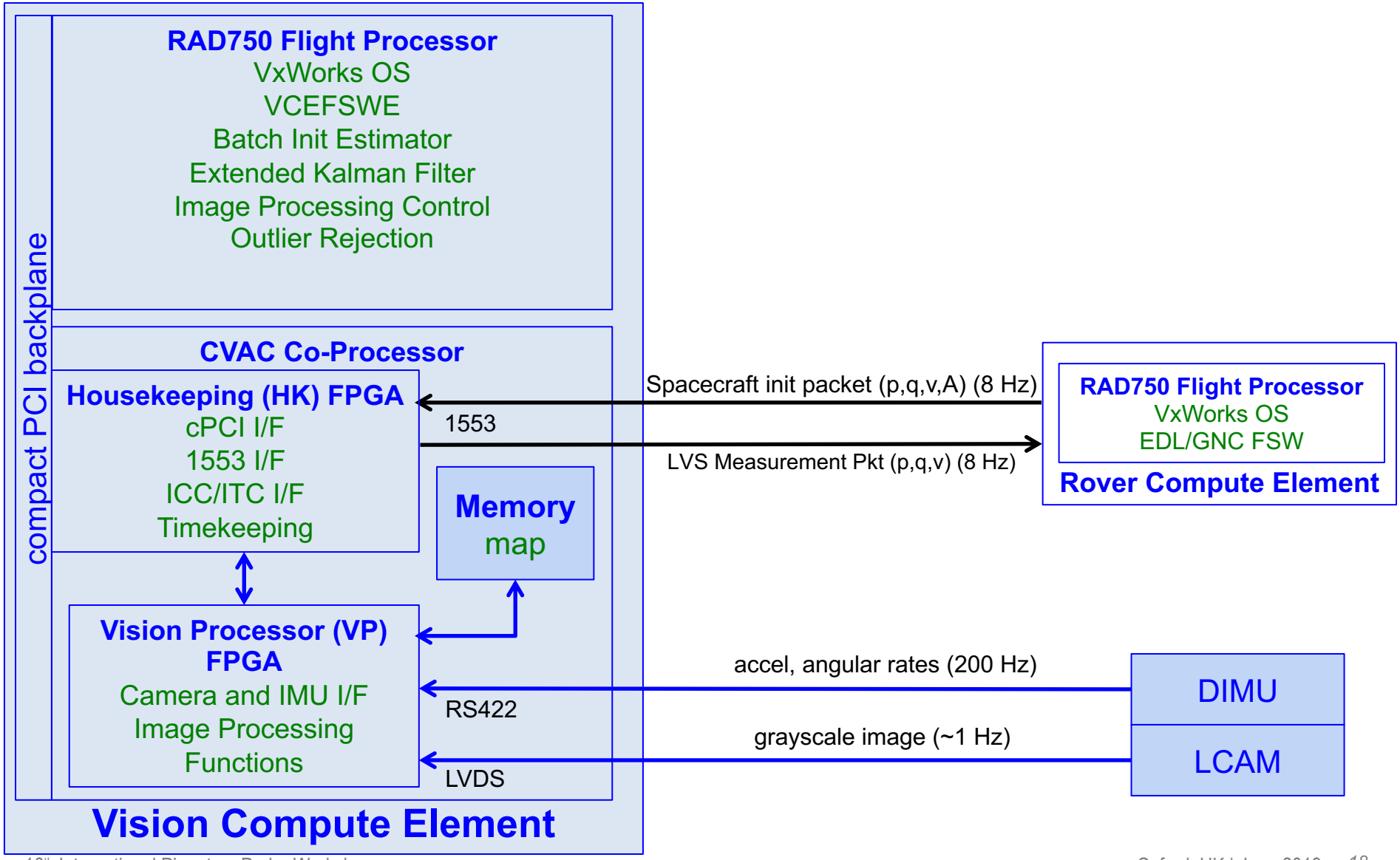


LVS V&V Status

		VENUE							
VnV Level	Unit Analysis &Test	Simulations			LVS Field Test	Hardware Testing			
		VCE FPGA Sim	VCEWSTS	LVSTS		VCE Bench	VCEFSWTB	LVSTB	ETL
L5 LVS				Not Begun	Complete			In Progress	
L6 GSE						Complete		Complete	
L6 MRL			In Progress				In Progress		
L6 VCEFSW	In Progress		In Progress				In Progress		
L6 MAP	In Progress								
L6 VCE						Complete			Complete
L7 CVAC						Complete			
L8 HK & VP FPGA		Complete							
L6 LCAM	Complete								
DIMU	Complete								

BACKUP

LVS Data Flow & Processing



List of Verification Activities

VA ID	Name	R4R Venue
318781	LVS Functional and Interfaces	LVSTB
318782	LVS Performance Test	LVSTB
595915	LVS Off-Nominal	LVSTB
319445	LVS Performance Analysis	LVSTS
595978	LVS Field Test	Helicopter

LVS Functional & Interfaces VA

- Description
  - Test LVS functionality and interfaces and show performance as expected
- Objectives
  - Verify LVS functionality by phase (Cruise, EDL and Surface)
  - Verify LVS internal interfaces (VCE <-> LCAM) and external interfaces (LVS <-> RCE) perform as required
- R4R Venue
  - LVSTB-2
  - Configuration
    - VCE EM + GSE
    - EM LCAM, EM DIMU
    - VCEFSWE 3.2
    - S/C bus model
- Success Criteria
  - LVS functional tests
    - All LVS functionality for all phases performs as required
  - LVS interfaces tests
    - All interfaces, power and data, perform as required
- Test Cases
  - 1553, ICC/ITC, DIMU, LCAM data interfaces
  - VCE and LCAM power interfaces
  - Phase specific functionality
    - Cruise: LVS checkout, updates of VCEFSWE image, VP FPGA image, map and parameters
    - EDL: All non-MRL EDL functionality
    - Surface: Data product retrieval
  - Sensor functionality
    - DIMU, LCAM
  - HWIL testing
  - Spacecraft commands and LVS telemetry (EVRs, EHA)

LVS Performance Test VA

- Description
  - Execute a series of hardware tests to verify and validate that LVS performs required functionality within time, accuracy and latency requirements
- Objectives
  - Verify Map Relative Localization (MRL) meets time and accuracy requirements
  - Verify LVS boot, shutdown and MRL initiation meet time requirements
  - Verify all latencies are within requirements
  - Validate LVS performance as expected
- R4R Venue
  - LVSTB-2
  - Configuration
    - VCE EM + GSE
    - EM LCAM, EM DIMU
    - VCEFSWE 3.2
    - Gimbal and target board
    - S/C bus, S/C-GN&C, DIMU, LCAM, MAP and heatshield models
    - Motion Trajectory Generator
- Success Criteria
  - LVS performs require functionality within time, accuracy and latency requirements
- Test Cases
  - Map Relative Localization Performance
    - Reduced and Nominal
  - Boot, Shutdown and MRL Initiation Time Performance
    - Nominal boot, fast reboot, time to shutdown and MRL initiation time within operational envelope
  - Latency Tests
    - Transition to transmitting measurement packets, measurement packet latency, LCAM image latency

LVS Off-Nominal VA

- Description
  - Execute a series of tests that create off-nominal conditions and examine LVS response to those conditions
- Objectives
  - Verify correct operation of watchdog timers
  - Verify LVS responds as expected to various software and hardware failures
- R4R Venues
  - LVSTB-2, LVSTS
  - Configuration
    - VCE EM + GSE
    - EM LCAM, EM DIMU
    - VCEFSWE 3.2
    - S/C bus, S/C-GN&C, DIMU, LCAM, MAP and heatshield models
    - Motion Trajectory Generator
- Success Criteria
  - LVS performs as expected in response to off-nominal conditions
- Test Cases
  - Watchdog Timers
    - VCEFSWE, VCE Remote Terminal
  - VCE Failures
    - Unrecoverable error response, VP FPGA auto-load failure recovery
  - LCAM Failures
    - Unresponsive LCAM
    - Bad LCAM image (replicated, corrupted, lost)
  - DIMU Failures
    - Bad DIMU data (replicated, corrupted, lost)
  - VCEFSWE Failure
    - Incorrect execution failure response (missing tasks, non-responsive tasks)
  - MRL Failure to Produce Solution
    - LCAM image exposure adjustment, retry COARSE mode
  - Spacecraft Initialization Packet Failures
    - Bad spacecraft initialization packet (replicated, corrupted, lost)

LVS Performance Analysis VA

- Description
  - Execute a series of Monte Carlo simulations to verify performance of LVS over and beyond its operational envelope during EDL
- Objectives
  - Verify LVS performance meets requirements given expected initialization and operational uncertainty
  - Develop statistical measure of LVS performance, including sensitivity to dispersed initialization and operating conditions
  - Validate LVS performance as expected
- R4R Venue
  - LVSTS
  - Configuration
    - VCESim (VCE device model)
    - S/C bus, S/C-GN&C, DIMU, LCAM, MAP and heatshield models
    - Motion trajectory generator
    - VCEFSWE 3.2
    - S/C bus model
- Success Criteria
  - LVS performance as required over conditions that span the LVS operational envelope during EDL
- Test Cases
  - Nominal Zero Mean, used as starting point for sensitivity studies
  - Sensitivity Studies, provides performance assessment for various parameters over and beyond operational envelope
  - Worst Case Studies, provides performance assessment over worst case in operational envelope

LVS Field Test VA

- Description
  - Execute Captive Carry helicopter field test in a real-world environment over Mars-relevant terrain with higher-fidelity flight dynamics than can be achieved in a lab environment
- Objectives
  - Perform a statistically significant number of real-time LVS position estimations in flight
    - for comparison against LVSTS position estimates
    - for sensitivity studies
  - Collect synchronized LCAM, DIMU and ground truth data that spans the LVS operation envelope
    - for sensor model certification
    - for V&V of flight delivery with vertical motion
  - Perform end-to-end LVS processing in flight
    - for test as you fly
  - Perform off-nominal testing and collect off-nominal data
    - for on-line & off-line fault protection testing
- R4R Venue
  - Helicopter
  - Configuration
    - VCE EDU4 + GSE
    - EM LCAM, EM DIMU
    - VCEFSWE 3.1
    - Gimbal
    - S/C bus model
    - GPS/INS
- Success Criteria
  - LVS meets required EDL functionality and performance within time and latency requirements
  - LVSTS certified successfully
- Test Cases
  - Map Relative Localization Performance
    - Reduced and Nominal